(4)

David Taylor Research Center
Bethesda, MD 20084-5000

AD-A226 499

DTRC-SME-90/54 June 1990

Ship Materials Engineering Department
Research & Development Report

Intelligent Processing for Spray Metal Manufacturing

by
Angela L. Moran
Dawn R. White

DTIC
S ELECTE
SEP 1 4 1990
D

90 09 13 116

CODE 011   DIRECTOR OF TECHNOLOGY, PLANS AND ASSESSMENT

      12   SHIP SYSTEMS INTEGRATION DEPARTMENT

      14   SHIP ELECTROMAGNETIC SIGNATURES DEPARTMENT

      15   SHIP HYDROMECHANICS DEPARTMENT

      16   AVIATION DEPARTMENT

      17   SHIP STRUCTURES AND PROTECTION DEPARTMENT

      18   COMPUTATION, MATHEMATICS & LOGISTICS DEPARTMENT

      19   SHIP ACOUSTICS DEPARTMENT

      27   PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT

      28   SHIP MATERIALS ENGINEERING DEPARTMENT

DTRC ISSUES THREE TYPES OF REPORTS:

1. **DTRC reports, a formal series,** contain information of permanent technical value. They carry a consecutive numerical identification regardless of their classification or the originating department.

2. **Departmental reports, a semiformal series,** contain information of a preliminary, temporary, or proprietary nature or of limited interest or significance. They carry a departmental alphanumerical identification.

3. **Technical memoranda, an informal series,** contain technical documentation of limited use and interest. They are primarily working papers intended for internal use. They carry an identifying number which indicates their type and the numerical code of the originating department. Any distribution outside DTRC must be approved by the head of the originating department on a case-by-case basis.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	

4. PERFORMING ORGANIZATION REPORT NUMBER(S) DTRC-SME-90-54	5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION David Taylor Research Center	6b. OFFICE SYMBOL *(If applicable)* DTRC 2812	7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)* Bethesda, MD 20084-5000	7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION David Taylor Research Center	8b. OFFICE SYMBOL *(If applicable)* Code 0115	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)* Bethesda, MD 20084-5000	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*

Intelligent Processing for Spray Metal Manufacturing

12. PERSONAL AUTHOR(S)
Angela L. Moran, Dawn R. White

13a. TYPE OF REPORT Research & Develop.	13b. TIME COVERED FROM 10/88 TO 9/89	14. DATE OF REPORT *(Year, Month, Day)* June 1990	15. PAGE COUNT 19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A program to implement real time sensing and control of spray formed preform conditions is underway at the David Taylor Research Center. The objective of the program is to develop sensor and control technology to monitor the critical process conditions and to modify parameters during the spray forming process to produce components with repeatable microstructural quality. This task has been divided into two phases, the first of which entails development of sensors and controls to monitor and correct simulated process conditions. In the second phase, the selected sensors and controls will be combined with actuators for integration with the DTRC equipment to allow for the production of nonsymmetric preforms.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Angela L. Moran	22b. TELEPHONE *(Include Area Code)* (301)267-2374	22c. OFFICE SYMBOL Code 2812

DD Form 1473, JUN 86   *Previous editions are obsolete.*   SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 1-2812-001 of the Submarine Materials Block. The program manager for this task is Mr. Ivan L. Caplan, DTRC, Code 0115

CONTENTS

FIGURES

TABLES

INTELLIGENT PROCESSING
FOR SPRAY METAL MANUFACTURING

Angela L. Moran
David Taylor Research Center
Metals and Welding Division
Annapolis, Maryland

Dawn R. White
MTS Systems Corporation
Advanced Technology Development Division
Minneapolis, Minnesota 55424

SUMMARY

A program to implement real time sensing and control of spray formed preform conditions is underway at the David Taylor Research Center. The objective of the program is to develop sensor and control technology to monitor the critical process conditions and to modify parameters during the spray forming process to produce components with repeatable microstructural quality. This task has been divided into two phases, the first of which entails development of sensors and controls to monitor and correct simulated process conditions. In the second phase, the selected sensors and controls will be combined with actuators for integration with the DTRC equipment to allow for the production of nonsymmetric preforms.

INTRODUCTION

High deposition rate spray forming is a new technology which is under development to reduce the cost and improve the workability and mechanical properties of a spectrum of engineering alloys. In the spray deposition process, a stream of molten metal is atomized by an inert gas, producing a spray of liquid droplets which are cooled by the gas and accelerated towards a substrate, where they consolidate to form a fully dense deposit. The process improves on ingot metallurgy in that a rapidly solidified, grain-refined microstructure with limited segregation is produced. Spray forming exhibits the beneficial characteristics of powder metallurgy processing without the numerous stages involved, such as powder production, storage and handling, sintering and hot consolidation. A program at the David Taylor Research Center sponsored by the Office of Naval Technology evaluated the feasibility of utilizing (Osprey) spray forming to produce Alloy 625 (Ni-Cr-Fe-Mo) piping. The results of this program showed that fully dense preforms could be sprayed and roll extruded into piping with properties equivalent to conventionally made piping at substantially reduced costs[1]. Cost savings projections for simple shapes such as piping tubulars produced via spray forming are as high as 30 - 50%

1

versus conventional processing technology. The technology is alloy non-specific and therefore is applicable to a wide range of metallic systems.

Currently, however, spray forming technology is limited to symmetrical shapes and requires trial runs to establish processing parameters. Development of in-process controls to minimize the trial and error method for establishing processing parameters would further reduce costs and make spray forming more commercially attractive. More importantly, it would provide a cost-effective means to produce a variety of quality near net shaped products not now possible by spray forming. Such components could be substituted for higher priced forgings or lower performance castings. Additional benefits are in the form of improved domestic capability through technology transfer, the opportunity to produce shapes and material combinations not currently feasible, the opportunity to develop improved performance/lower cost components for military applications at an accelerated rate, and advanced sensors for potential use in other metals processing applications.

RESEARCH AND DEVELOPMENT STATUS

A program to implement real time sensing of preform temperature, rate of growth, and quality (as indicated by surface properties) has been undertaken at the David Taylor Research Center. The objective of the program is to develop sensor and control technology to monitor the critical process conditions and to modify parameters during the process to produce components with repeatable microstructural quality. This task has been divided into two phases, the first of which entails development of sensors and controls to monitor and correct simulated process conditions. In the second phase, the selected sensors and controls will be combined with actuators for integration with the DTRC equipment. Figure 1 is a diagram of the integrated sensing and control system as adapted to the spray forming process

A sensor development plan has been established and candidate optical and infrared technologies have been evaluated. Laser striping and oblique lighting were selected as the most promising techniques for evaluating preform quality during deposition and have been incorporated into the data acquisition system and spray forming instrumentation. Processing algorithms for extraction of information from the visual image are under development. An IR camera capable of providing values for preform surface temperature has been added.

The control system has been divided into subsystems including spray planner, spray modeler, motion planner, run simulator and run manager. The spray planner and spray modeler use a database of past run experiences and an expert system shell to develop the process recipe for each new run. The run recipe contains the process set points as a function of time. Part motion is defined by the motion planner which uses information

2

from previous runs to generate a path for the manipulator. The
run is simulated by the simulator subsystem so that preform
growth and shape can be evaluated before actual execution.
Expected values for shape, surface condition and temperature are
utilized by the run manager to guide the process during the
actual spray forming run. Hardware and software for each
subsystem are nearing design completion. Sensor data is used by
a fuzzy logic based intelligent controller to make adjustments to
primary process parameters such as atomization gas pressure,
droplet flight distance and melt flow rate. These adjustments
are made in small increments, and sensor feedback determines
whether appropriate responses are obtained in the process. The
goal is to maintain a quasi-static process state in which
appropriate deposition layer thickness and temperature result in
a fully dense preform with a fine, equiaxed grain structure.

The spray collector's movement will be expanded beyond the
current one-axis linear motion and one-axis rotational movement.
Expansion will include consideration of coordination of movement
with the spray deposition process, inertial and unbalanced force
effects and motions required to form currently unobtainable
nonsymmetric shapes. The manipulator will use hydraulic
actuators and will have five axes of motion including x, z, wrist
roll, wrist pitch, and tool roll with an optional y axis that can
be added as required.

In addition, a detailed, empirical process data base has
been developed which includes all monitorable process conditions
(such as alloy type, microstructural quality and preform
soundness). A long term goal of the program is to
establish the relationship between preform microstructure and
quality with processing practices in order to optimize and
control the spray forming method.

APPLICATION OF INTELLIGENT CONTROL CONCEPTS

The spray forming process is complex, and process models
which can be readily used to control material quality and
characteristics using conventional closed loop control systems do
not exist. Indeed, for the purposes of process control, spray
forming can be viewed as three discrete subprocesses[2]:

* atomization (spray generation)
* droplet consolidation (deposit formation)
* solidification (microstructure evolution)

Each of these is a multiple input, multiple output, non-linear
control problem with its own thermal conditions and kinetics[3].
The heat transfer models for these subprocesses are not suitable
for control, although research efforts in model reduction methods
show promise and may bring advances in the area in the next few
years[4].

In general, spray forming is controlled through the use of

3

"local" control loops, single input, single output, linear closed loop controllers for basic process parameters such as melt temperature (super heat), atomizing gas pressure, metal flow rate (gas overpressure), withdrawal rate, etc. These local control loops are typically managed by programmable logic controllers (a Gould-Modicon in the case of the DTRC spray forming unit). However, while these process parameters can be controlled fairly precisely, the relationship between basic process parameters and preform quality, as defined by microstructure, homogeneity and freedom from porosity or cracking, is not well understood. If new alloys or shapes are to be spray formed, extensive trial and error experimentation is required to establish the range of suitable operating parameters required to produce quality preforms.

The objective of intelligent control is to establish relationships, or mappings between the locally controlled, primary process parameters, and indicators of final part quality, which can be sensed and controlled in real time[5]. These mappings may be represented by mathematical models, expert systems, neural networks, or other forms of knowledge representation. In some cases, more than one type of control method may be employed[6]. In the case of spray forming it is known that expert operators typically observe the preform during spraying, and that surface roughness and "glitter" (a phenomenon associated with recalescence produced by the loss of latent heat of fusion and related to part surface temperature and liquid fraction) are two measurable quantities related to final preform quality. Operators modify the primary process parameters in response to visually observed changes in the secondary or dependent parameters, surface roughness and glitter.

These dependent parameters can be sensed in real time using a combination of techniques, including structured light, grey scale vision, and thermography. These are discussed in detail in the section below. A method is then needed to relate secondary parameter sensed values to control actions to be implemented on locally controllable primary process parameters. In well characterized processes, this will be an invertable mathematical model describing the relationship between the sensed parameter value, primary parameter values, and some measurement of product quality (e.g. grain size, strength, etc.). Since spray forming does not fall into this category, means of emulating the operators' knowledge without the use of mathematical models must be employed. Fuzzy logic control was selected, as it provides a way of representing inexact process knowledge as well as resolving conflicts in sensor and control data through the use of fuzzy set theory. Fuzzy control is discussed in more detail below. Finally, an advanced manipulation capability is critical to the application of intelligent control to spray forming. Droplet flight distance strongly affects the temperature and liquid fraction of the material deposited at the preform surface, which is in turn a primary factor involved in preform microstructure, density and freedom from cracking. In order to

4

fabricate complex shapes it must be possible to vary ram position rapidly in order to maintain a constant flight distance. Normal inconsistencies in local deposition rates result in a need for sophisticated control. These factors are also considered in detail below.

SENSORS

Sensing the basic process parameters such as melt temperature, atomizing gas pressure, metal flow rate and withdrawal rate can be accomplished with conventional, commercially available sensors. Measuring preform growth rate and shape, and quantifying preform surface roughness and quality in real time, however, have proven to be challenging sensor tasks.

All sensing methods that require contact with the preform are precluded by the semi-liquidous state of the preform. Sonic and ultrasonic sensors are highly unstable in the dynamic thermal environment of the spray forming chamber. As a result, optical sensors have been selected.

A single optical sensor has been developed that simultaneously measures preform shape, preform growth rate and preform surface roughness. The sensor, shown schematically in Figure 2 comprises a single-frequency argon laser and electronically shuttered, charged coupled device (CCD) video camera which views the image of the laser beam on the preform during deposition. Appropriate software and hardware are used to analyze the images from the video camera and convert the information into a form compatible with the controller.

The optical sensor operates on the principle of optical triangulation. Any change in the height of the preform surface will result in a translation of the laser stripe image as seen by the video camera. The overall translation of the laser stripe image is proportional to the overall change in the height of the preform and the rate of growth. The average rate of growth can be determined by numerically fitting a straight line to the laser stripe image and calculating the shift in the center point of the line.

The shape of the laser stripe image is dependent upon the shape of the preform. For example, the image of the laser stripe on a flat surface will be a straight line and the image on a rounded surface will be a curved line. By numerically fitting the laser stripe to a higher order polynomial, the coefficients of the polynomial can be used to quantify the degree of curvature of the preform surface.

The surface roughness of the preform is directly related to the amplitude and frequency of the spatial modulation of the laser stripe image. Information is extracted from the laser image through the use of Fast Fourier Transforms (FFTs). The

FFTs are a series of sine waves that when summed result in the original shape of the laser image and indicate the texture and quality of the preform during deposition. Lower frequency terms of the FFTs can be averaged as an indicator of macro-roughness and higher frequency terms can be averaged as an indicator of micro-roughness.

FUZZY LOGIC CONTROLLER

Primary process parameters (melt superheat, primary and secondary atomizing gas pressures, flight distance, preform withdrawal rate, etc.) affect each of the spray forming subprocesses (atomization, consolidation and solidification) in ways which can be understood qualitatively in terms of well defined metallurgical phenomena. While mathematical models are now being developed of the spray forming process (and subprocesses), these remain too complex for application to real time control[7,8]. However, our qualitative understanding of the mechanisms operating in each subprocess can be embedded in rules relating various primary process parameters to sensor data and desired part properties. Fuzzy methods are well suited to metallurgical processes, many of which, like spray forming, are actually multiple coupled subprocesses, and in which it may be difficult to resolve information from the multiple sensors required for monitoring[9,10].

Specifically, the Fuzzy Logic Controller (FLC) will assess the status of each run during processing and output control values to help correct for various anomalies that are inherent to the spray forming process. The FLC will accomplish this by executing Fuzzy Subset theory logic operations contained in an operator selected Rule Set. Figure 3 is the control flow diagram for the FLC. The inputs and outputs to the Fuzzy Logic Controller are based on critical, definable process parameters that can be quantified. Inputs include surface roughness (and quantifiable variations such as macro-roughness and micro-roughness), rate of deposition, surface temperature, metal flow rate, secondary gas pressure, and motion profile variations. Every cycle, the FLC reads in control inputs from the run manager database. The rate at which the FLC will operate is 10 hertz (minimum). Once the control inputs have been read in, the FLC goes through each rule contained in the system. Rules will be in the form of IF - THEN conditional statements, such as the following:

"if macro-roughness & micro-roughness are present and micro-roughness is decreasing then maintain secondary gas pressure"

In fuzzy algorithm nomenclature, each term of this statement is called a fuzzy set (i.e. there are four fuzzy sets in the above rule: macro-roughness, micro-roughness, micro-roughness is decreasing, and maintain secondary gas pressure). For each rule, the FLC will perform the corresponding Fuzzy logic to determine a value that can be related to a desired output, and rules can be

thought of as being grouped according to the outputs they affect. Given the above outputs, there are three groups of rules: rules affecting metal flow rate, secondary gas pressure and motion profile corrections.

The fuzzy logic controller provides a means of analyzing sensor data and making variable process corrections in much the same way that a skilled operator might, while the protocols of fuzzy set theory and membership functions permits us to deal implicitly with transient phenomena and conflicting data.

MANIPULATOR AND MOTION CONTROL

A high performance manipulator and flexible motion controller are required to produce asymmetric shapes and to enable droplet flight distance to act as a control variable. Some of the shapes to be spray formed include elbows, nozzles and hemispheres in addition to the pipe, billet and plate that can be spray formed using existing technology. Parts weighing up to 150 pounds and measuring up to 24 inches in length can be accommodated. The motion and acceleration requirements for these shapes drive the manipulator design. In addition, the motion controller and manipulator must permit modifications during runs based on the fuzzy logic controller inputs.

The capabilities of the manipulator are defined in Table I. The axes of motion are controlled by a multi-variable control scheme, required by the cross-coupling between the three revolute joints, which operates at up to 500 Hz. Inputs to the motion controller include motion profiles created off-line as part of the planning process, motion profile corrections output by the fuzzy logic controller, profiles for the gains in the multi-variable controller and multi-variable gain profile corrections output by the fuzzy logic controller. The outputs from the motion controller in response are manipulator position commands to the hydraulic motors and manipulator position feedback to the run database.

Initially, part motion profiles are developed as a planning and simulation activity and represent a best guess estimation of the optimal approach. Based on sensor data about part quality, these profiles can be corrected during an actual run. As pounds of metal are added to the manipulator, the dynamics of the mechanical system will change significantly over the course of a run. The gains of the motion controller will change as a result. These changes can be input as gain profiles during planning and can be modified by the fuzzy logic controller. This combination of mechanical performance, high update rate and control flexibility will enable the manipulator to support the requirements for spraying of asymmetric shapes.

CONCLUSION

A program to develop sensor and control technology for real time implementation with spray forming has been undertaken at the David Taylor Research Center. The objective of this effort is to insure reproducibility and quality of spray formed products and to expand the capability to manufacture asymmetric shapes. Sensor data is used by a fuzzy logic intelligent controller to make adjustments to spray forming process parameters during preform deposition. Advanced manipulation capabilities are required to produce asymmetric components.

ACKNOWLEDGEMENTS

REFERENCES

1. Moran, A.L. and W.A. Palko, "Spray Forming Alloy 625 Marine Piping", J. Metals, Vol. 40, No. 12, December, 1988, p. 12-15.

2. Mathur, P. and D. Apelian, "Spray Casting: A Review of Technological and Scientific Aspects", Book Series on Powder Metallurgy, Vol.3 Current Status of P/M Technology, I. Jenkins and J.V. Wood, eds., Institute of Metals, 1990.

3. Mathur, P. "Analysis of the Spray Deposition Process", Ph.D. Thesis, Drexel University, Philadelphia, 1988.

4. Shelton, P.R., Dynamic Systems Control, Wiley and Sons Publishers, 1988, Chapter 8.

5. Cook, G.E., K. Andersen and R.J. Barnett, "Feedback and Adaptive Control in Welding", Recent Trends in Welding Science and Technology, S. David and J. Vitek, eds., ASM International, 1990.

6. White, D.R. and J.E. Jones, "A Hybrid, Hierachical Controller for Intelligent Control of Welding Processes", Recent Trends in Welding Science and Technology, S. David and J. Vitek, eds., ASM International, 1990.

7. Apelian, D., A. Lawley, G. Gillen and P. Mathur, "Spray Deposition: A Fundamental Study of Atomization", ONR Technical Report, September 1985.

8. Apelian, D., A. Lawley, G. Gillen and P. Mathur, "Spray

Deposition: A Fundamental Study of Droplet Impingement, Spreading and Consolidation", ONR Technical Report, September 1986.

9. Li, Y.F. and C.C. Lau, "Development of Fuzzy Algorithms for Servo System", IEEE Control Systems Magazine, April, 1989, pp. 65-71.

10. Newell, R.B., Applied Process Control, Prentice Hall Publishing Co., Sydney, 1989.

AUTHOR BIOGRAPHIES

Angela L. Moran received her Ph.D. in materials science and engineering from the Johns Hopkins University. She is currently a materials engineer in the Metals and Welding Division of the David Taylor Research Center, Department of the Navy, in Annapolis, Maryland. Dr. Moran is a member of TMS.

Dawn R. White received her Ph.D. in mechanical engineering from the University of Illinois. She is a senior engineer in the Advanced Technology Development Division of MTS Systems Corporation, Minneapolis, Minnesota.
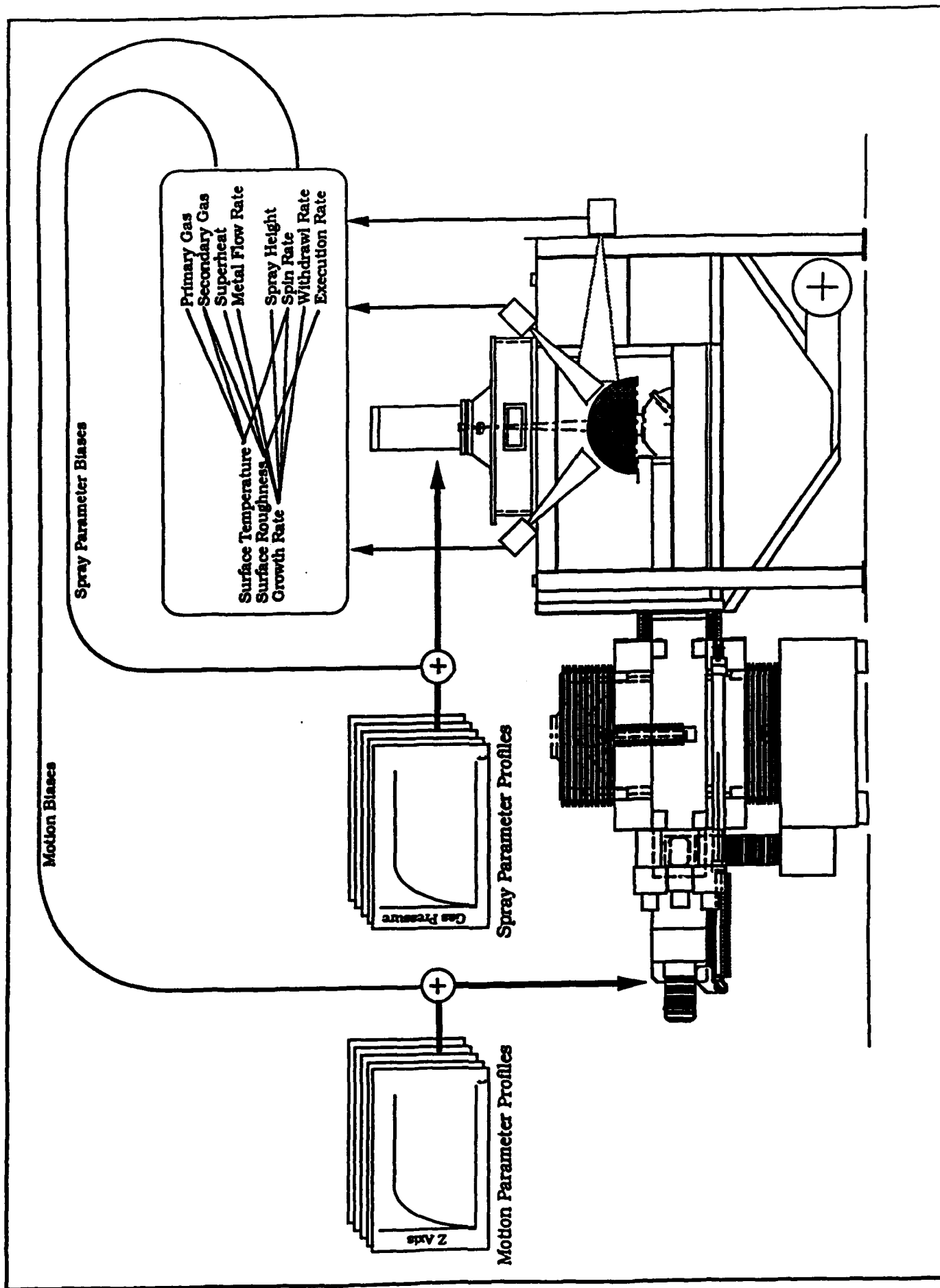
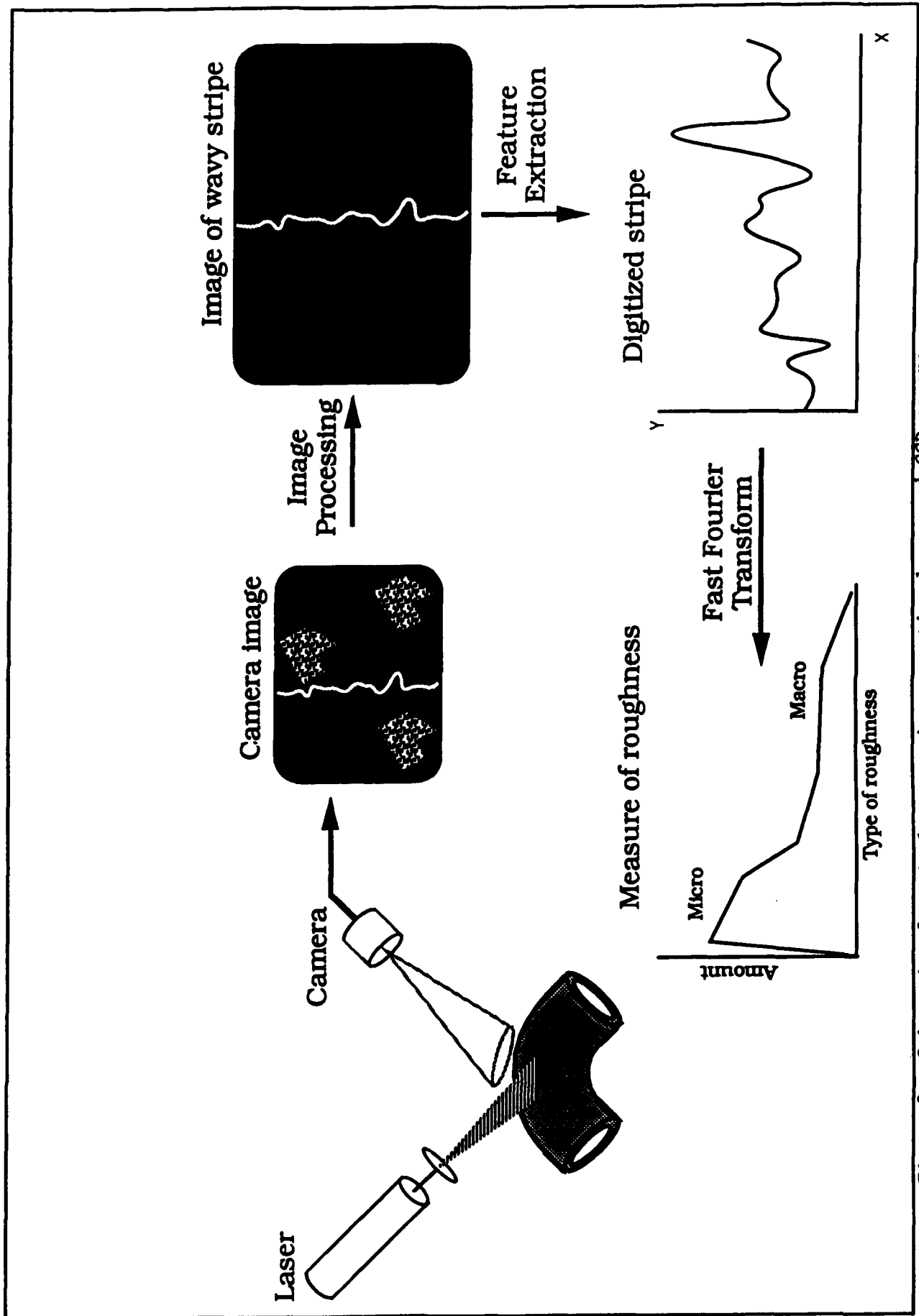Figure 1. Integrated sensing and control system for spray forming.

10

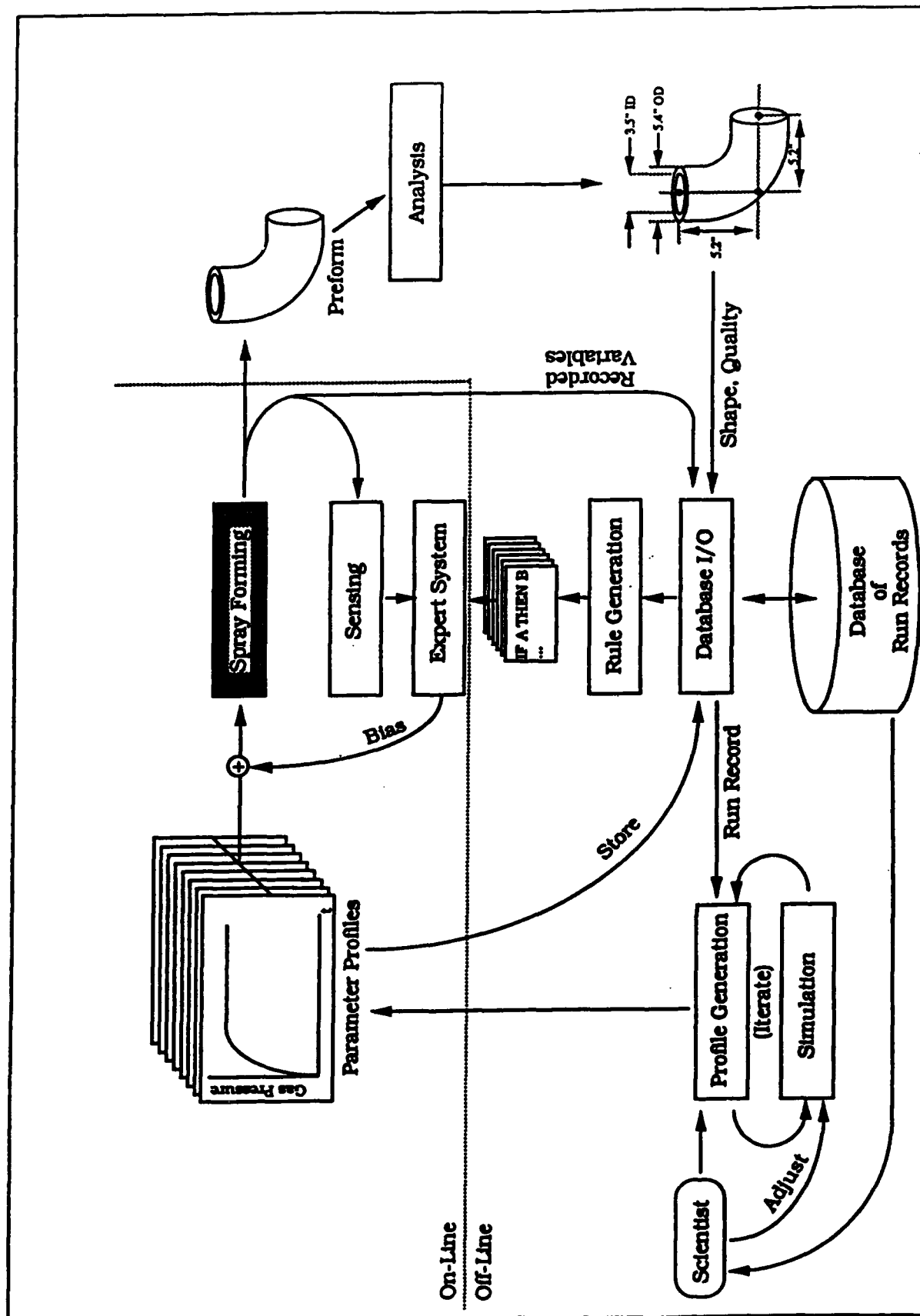Figure 2. Schematic of optical sensor incorporating laser and CCD camera.

Figure 3. Control flow diagram for the fuzzy logic controller.

Table I. Motion Requirements and Design

Motion requirements:[*]

Axis	Range	Maximum Velocity	Maximum Acceleration	Maximum Torque	Resolution
X	34 inches	72 in/sec	64 ft/sec^2	n/a	0.001 inches
Y	16 inches	10 in/sec	9.7 ft/sec^2	n/a	0.001 inches
Z	18 inches	10 in/sec	9.7 ft/sec^2	n/a	0.001 inches
Tool roll	360 degrees	270 RPM	148 rad/sec^2	800 in-lbs	30 arc minutes
Pitch	+90,-90 deg.	10 RPM	10 rad/sec^2	3000 in-lbs	30 arc minutes
Wrist roll	360 degrees	270 RPM	148 rad/sec^2	3000 in-lbs	30 arc minutes

[*]Velocity values are peak momentary values during cyclic motion. Acceleration values shown are for representative preform shapes.

Motion design:

Power:	• Hydraulic (all axes) • 30 - 40 gallons per minute flow capacity
Linear motion design:	• Hydraulic cylinders with servovalves • Temposonic linear tranducers • Precision linear bearings
Rotary motion design:	• Axial vane servo motors with servovalves • Resolver feedback • Remotely driven, geared three axis wrist
Overall dimensional envelope:	• 108" long x 50" wide x 70" high

INITIAL DISTRIBUTION

Copies		CENTER DISTRIBUTION		
		Copies	Code	Name
12 DTIC		1	0113	Douglas
		1	0115	
1 ONT		1	28	Wacker
1 ONT 225		1	283	Singerman
		1	284	Fischer
		1	2801	Crisci
		1	2801	Ventriglio
		1	2802	Morton
		1	2803	Cavallaro
		1	2809	Malec
		1	281	
		1	2812	
		10	2812	Moran
		10	3411.1	
		1	342.1	TIC (C)
		1	342.2	TIC (A)
		1	3431	Office Services